

# Effects of vector-control interventions on changes in risk of malaria parasitaemia in sub-Saharan Africa: a spatial and temporal analysis



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## Summary

**Background** In the past decade, decreases in clinical episodes and deaths due to malaria have been mainly associated with the expansion of vector-control measures, such as insecticide-treated bednets and indoor residual spraying. Malaria indicator surveys gather information about key malaria indicators through national representative household surveys. We aimed to estimate changes in risk of malaria parasitaemia at high spatial resolution in sub-Saharan Africa, and to quantify the effects of malaria interventions at national and subnational levels.

**Methods** In this spatial and temporal analysis, we analysed data from the six sub-Saharan countries that had publicly available data from two malaria indicator or demographic and health surveys with malaria measurements done in 2006–08 and 2010–12: Angola, Liberia, Mozambique, Senegal, Rwanda, and Tanzania. We used Bayesian geostatistical models to estimate the present malaria risk and to establish the change relative to the period between the last two national surveys. We applied Bayesian variable selection procedures to select the most relevant insecticide-treated-bednet measure for reducing malaria risk, and did spatial kriging over the study region to produce intervention coverage maps. We estimated the contribution of bednets and indoor residual spraying on changes in malaria risk, after adjustment for climatic and socioeconomic factors. Spatially varying coefficients of intervention coverage enabled estimation of their effects at subnational level.

**Findings** In all countries, the probability of decrease in parasitaemia varied substantially between regions. Insecticide-treated bednets were an important intervention for reducing malaria risk, according to different definitions of coverage. An overall effect of insecticide-treated bednets at country level was significant only in Angola ( $-0.64$ , 95% credible interval  $-0.98$  to  $-0.30$ ) and Senegal ( $-0.34$ ,  $-0.64$  to  $-0.05$ ); however, in all countries, we detected significant effects of bednets and indoor residual spraying at local level.

**Interpretation** The described methodology is useful for the identification of regions where changes in malaria risk have taken place, and to describe the geographical pattern of malaria. Intervention effects vary in space, which might be driven by local endemicity levels. The produced maps provide a visual aid for national malaria control programmes to identify where targeted strategies and resources are most needed or likely to have the greatest effect on reducing the risk of parasitaemia.

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## Introduction

Malaria reduction is part of the Millennium Development Goals (MDGs), with an aim to halve malaria incidence by 2015, compared with 1990.<sup>1</sup> To monitor and assess progress towards this target, a set of indicators has been proposed: incidence and death rates associated with malaria, proportion of children younger than 5 years sleeping under insecticide-treated bednets, and proportion of children younger than 5 years with fever who are treated with appropriate antimalarial drugs.<sup>1</sup> Renewed interest in malaria elimination and eradication has led to the definition of new targets.<sup>2</sup> In 2010, the Global Malaria Action Plan<sup>3</sup> called for rapid scale-up to achieve universal coverage with some form of vector control.

The Roll Back Malaria Partnership developed malaria indicator surveys to coordinate global efforts to fight

malaria. Unlike historical malaria parasitaemia surveys, which are heterogeneous in survey seasons and in age groups sampled across locations, malaria indicator surveys are nationally representative and standardised in terms of design, survey questionnaire, implementation season, and population included. Malaria indicator surveys are based on a two-stage cluster sampling design to obtain national and regional or provincial data from a representative sample of respondents. In most countries, census-based enumeration areas stratified by rural or urban province are selected in the first stage and households are systematically sampled within enumeration areas in the second stage. Malaria indicator surveys are usually done during seasons of high malaria transmission. Household questionnaires are used to obtain information about ownership and use of

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insecticide-treated bednets, indoor residual spraying, prompt and effective treatment of fever in young children, prevention of malaria in pregnant women, and measurement of malaria parasites and anaemia in children younger than 5 years and pregnant women. Malaria indicator surveys and demographic and health surveys with malaria modules are designed to produce data that can be compared over time and across countries, and therefore provide the most precise benchmark of progress towards international targets.<sup>4</sup>

Malaria indicator surveys, demographic and health surveys, and multiple indicator cluster surveys have been used to estimate coverage of insecticide-treated bednets in several sub-Saharan countries.<sup>5–7</sup> Ownership indicators have been considered, such as the proportion of households with at least one insecticide-treated bednet (or one net for every two people), as have use indicators—ie, the proportion of the population (or children or pregnant women) who slept under an insecticide-treated bednet the night before the survey. However, estimation of bednet coverage through national household surveys presents some challenges. For instance, national estimates could be underestimated or overestimated if the actual population at risk of developing malaria (ie, the level of endemicity) is not taken into account. Seasonality can represent an additional source of bias if surveys are done during dry and hot months (eg, because of issues of accessibility to remote areas) when people are less likely to sleep under bednets.<sup>7</sup>

By inclusion of parasitaemia data, malaria indicator surveys enable assessment of the effect of several factors, including malaria control strategies, on health outcomes under real-world conditions.<sup>8</sup> The effectiveness of insecticide-treated bednets for prevention of malaria transmission has been shown in a systematic review and meta-analysis of randomised controlled trials,<sup>9</sup> in which regular use of bednets reduced all-cause child mortality by roughly 20% in malaria-endemic regions and decreased malaria episodes by half. The effect of different control strategies on prevention of malaria has also been assessed through simulation of different settings and scenarios with mathematical models.<sup>10–12</sup>

Geostatistical models have been used to analyse malaria indicator surveys in different African countries, with the production of spatial estimates of disease risk and the number of infected children younger than 5 years.<sup>13–18</sup> These models estimate the spatial effects of bednet ownership and use after adjustment for climatic factors and socioeconomic indicators.

Geostatistical models represent the most appropriate method for analysis of data from malaria indicator surveys because they enable the relation between malaria prevalence and intervention strategies to be quantified, after adjustment for environmental factors and socioeconomic status, while allowing correlation across spatial locations. Maps provide a powerful visual aid for national malaria control programmes by identifying regions where targeted strategies and resources are most

needed or most likely to have the greatest effect. We did a spatial and temporal analysis to estimate changes in malaria parasitaemia risk across sub-Saharan Africa. Additionally, we quantified the spatial effects of control measures at national and subnational levels.

## Methods

### Data sources

We analysed survey data from the six sub-Saharan countries that had publicly available data from two malaria indicator or demographic and health surveys with malaria measurements done at different times (2006–08 and 2010–12): Angola, Liberia, Mozambique, Senegal, Rwanda, and Tanzania. The appendix provides a detailed description of the included countries. We assessed coverage of insecticide-treated bednets by defining several ownership and use indicators derived from variables obtained through survey questionnaires, in line with previously published work.<sup>17</sup> We obtained data for coverage of indoor residual spraying from malaria indicator and demographic and health surveys that reported whether the house had been sprayed within the previous 12 months. A cluster-level socioeconomic proxy was defined as the proportion of the poorest (first wealth quintile) households within each cluster. We used information provided by mothers or caregivers in the questionnaire at the first administrative division level to calculate the proportion of fever episodes in the 2 weeks before the survey in children younger than 5 years who had received artemisinin combination therapies. We defined type of cluster area as a dummy variable (urban=1 vs rural=0). Other environmental and climatic factors were obtained at each cluster location by satellite imagery products (appendix).

### Statistical analysis

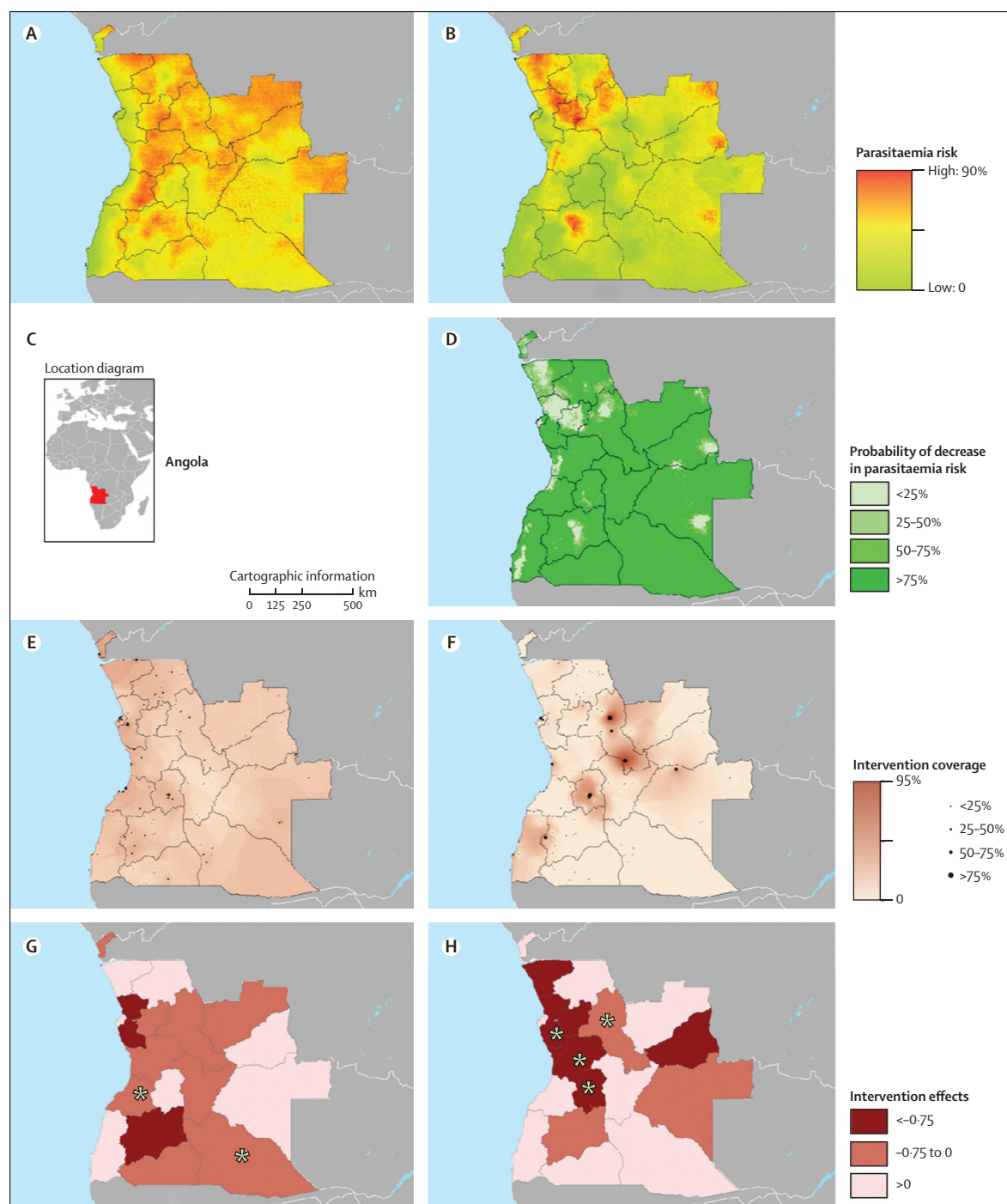
A geostatistical model was developed and fitted to assess the effect of climatic and environmental conditions on parasitaemia risk in each country. Each country was divided into a grid formed by 1 km resolution pixels. We used Bayesian kriging to predict malaria risk at high spatial resolution at the two survey time periods. Furthermore, we estimated the probability of parasitaemia risk reduction, the total number of children infected per survey period, and the difference in the total number of children infected between the two periods. We obtained estimates at pixel level and aggregated them by country. We used population data from Afripop,<sup>19</sup> which consist of spatial estimations of number of children younger than age 5 years per km<sup>2</sup> in 2010. To estimate the effect of interventions, we modelled the change of parasitaemia risk (on the logit scale) as a function of the difference in climatic and seasonal conditions between the two survey timepoints and intervention coverage (ie, insecticide-treated bednets and indoor residual spraying), with adjustment for socioeconomic factors. To account for potential interactions with endemicity levels, we fitted a second model to estimate different intervention effects for

See Online for appendix

	Angola	Liberia	Mozambique	Rwanda	Senegal	Tanzania
<b>Seasonality of transmission</b>						
Rainy period	March–May; October–November	September–October	December–April	May–June; November–December	September– December	March–May; October–December
<b>First survey</b>						
Survey type	MIS	MIS	MIS	Interim DHS	MIS	AIS and MIS
Survey period	November, 2006– April, 2007	December, 2008– March, 2009	June, 2007– July, 2007	December, 2007– April, 2008	November, 2008– January, 2009	October, 2007– February, 2008
Number of locations	115	150	345	246	315	465
Number of households	1518	2712	..	3508	4523	9142
Parasitaemia prevalence	0.22 (0.17–0.27)	0.31 (0.28–0.34)	0.30 (0.27–0.33)	0.02 (0.01–0.02)	0.06 (0.05–0.07)	0.12 (0.11–0.14)
ITN ownership						
Proportion of households with at least one ITN	0.40 (0.35–0.46)	0.32 (0.29–0.33)	..	0.78 (0.76–0.80)	0.36 (0.33–0.38)	0.68 (0.66–0.71)
Proportion of households with at least one ITN for every two people	0.15 (0.12–0.17)	0.12 (0.10–0.13)	..	0.23 (0.21–0.25)	0.34 (0.32–0.35)	0.42 (0.38–0.45)
Mean nets-to-people ratio	0.21 (0.19–0.22)	0.16 (0.14–0.17)	..	0.24 (0.22–0.28)	0.38 (0.31–0.44)	0.38 (0.33–0.41)
ITN use						
Proportion of children aged 0–59 months who slept under an ITN the night before the survey	0.37 (0.32–0.39)	0.35 (0.33–0.36)	..	0.33 (0.31–0.35)	0.42 (0.38–0.43)	0.55 (0.51–0.57)
Proportion of people who slept under an ITN the night before the survey	0.23 (0.21–0.25)	0.26 (0.24–0.27)	..	0.21 (0.19–0.23)	0.38 (0.33–0.39)	0.51 (0.49–0.53)
Indoor residual spraying	0.04 (0.01–0.06)	..	..	..	..	0.19 (0.09–0.27)
Proportion of fever episodes treated with any antimalarial combination therapy	0.22 (0.13–0.31)	0.58 (0.49–0.66)	..	0.05 (0.02–0.06)	0.08 (0.05–0.11)	0.53 (0.47–0.60)
Proportion of fever episodes treated with any artemisinin combination therapy	0.01 (0.00–0.02)	0.28 (0.23–0.33)	..	0.00 (0.00–0.01)	0.04 (0.02–0.06)	0.21 (0.17–0.25)
<b>Second survey</b>						
Survey type	MIS	MIS	DHS	DHS	DHS	AIS/MIS
Survey period	January, 2011– May, 2011	September, 2011– December, 2011	June, 2011– November, 2011	September, 2010– March, 2011	October, 2010– April, 2011	December, 2011– May, 2012
Number of locations	228	150	603	470	383	573
Number of households	8030	2140	3461	1472	7902	10 040
Parasitaemia prevalence	0.11 (0.08–0.14)	0.28 (0.25–0.32)	0.30 (0.28–0.33)	0.01 (0.00–0.02)	0.04 (0.03–0.05)	0.08 (0.07–0.09)
ITN ownership						
Proportion of households with at least one ITN	0.42 (0.38–0.44)	0.41% (0.37–0.43)	0.65 (0.61–0.68)	0.93 (0.91–0.95)	0.42 (0.38–0.43)	0.95 (0.88–0.96)
Proportion of households with at least one ITN for every two people	0.06 (0.04–0.08)	0.17% (0.15–0.22)	0.26 (0.25–0.28)	0.33 (0.31–0.35)	0.26 (0.25–0.27)	0.57 (0.51–0.59)
Mean nets-to-people ratio	0.09 (0.07–0.11)	0.17 (0.15–0.20)	0.24 (0.22–0.27)	0.37 (0.32–0.39)	0.29 (0.27–0.31)	0.48 (0.47–0.51)
ITN use						
Proportion of children aged 0–59 months who slept under an ITN the night before the survey	0.26 (0.21–0.28)	0.38 (0.37–0.41)	0.40 (0.38–0.42)	0.75 (0.71–0.77)	0.46 (0.42–0.47)	0.77 (0.73–0.78)
Proportion of people who slept under an ITN the night before the survey	0.19 (0.15–0.22)	0.32 (0.31–0.35)	0.32 (0.31–0.34)	0.15 (0.12–0.18)	0.41 (0.38–0.43)	0.69 (0.63–0.71)
Indoor residual spraying	0.07 (0.05–0.12)	..	0.24 (0.21–0.28)	..	0.05 (0.03–0.21)	0.22 (0.10–0.35)
Proportion of fever episodes treated with any antimalarial combination therapy	0.26 (0.18–0.34)	0.55 (0.50–0.60)	0.23 (0.14–0.31)	0.12 (0.05–0.18)	0.06 (0.04–0.09)	0.45 (0.35–0.54)
Proportion of fever episodes treated with any artemisinin combination therapy	0.20 (0.13–0.28)	0.41 (0.37–0.45)	0.14 (0.07–0.21)	0.11 (0.05–0.17)	0.02 (0.00–0.04)	0.30 (0.23–0.37)

Data are median (95% CI), unless otherwise stated. MIS=malaria indicator survey. DHS=demographic and health survey. AIS=AIDS indicator survey. ITN=insecticide-treated net.

**Table 1: Descriptive analysis of malaria survey data from six sub-Saharan African countries**



**Figure 1: Angola**

Predicted parasitaemia risk in 2006 (A) and 2010 (B), location diagram and cartographic information (C), probability of observing a decline in the period 2006–10 (D), ITN (E) and IRS (F) coverage maps, estimated effects of interventions: ITN (G) and IRS (H) (median plotted). ITN=insecticide-treated nets. IRS=Indoor residual spraying. \*Statistically significant effect.

each regional unit. To choose between the bednet coverage indicators, we defined a Bayesian variable selection procedure that selects only one (or none) bednet ownership indicator and one (or none) bednet use indicator separately for each country. The appendix provides further details about the methods and models used.

### Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

	Angola	Liberia	Mozambique	Rwanda	Senegal	Tanzania
<b>First survey</b>						
Covariate						
Rainfall	1.09 (0.01 to 2.18)	0.06 (−0.10 to 0.23)	0.43 (0.19 to 0.76)	−0.06 (−0.57 to 0.49)	0.91 (0.24 to 1.69)	0.49 (0.15 to 0.82)
NDVI	0.64 (−0.06 to 1.34)	0.08 (−0.10 to 0.25)	0.49 (0.21 to 0.65)	0.00 (−0.43 to 0.40)	0.59 (0.02 to 1.13)	0.39 (0.16 to 0.64)
Altitude	0.53 (−0.64 to 1.77)	0.11 (−0.11 to 0.32)	−0.21 (−0.69 to 0.23)	−1.05 (−2.14 to −0.07)	0.18 (−0.14 to 0.49)	−0.30 (−1.03 to 0.39)
LST night	0.95 (0.13 to 1.85)	−0.12 (−0.35 to 0.10)	−0.28 (−0.64 to 0.07)	−0.29 (−1.22 to 0.60)	0.24 (−0.36 to 0.78)	0.18 (−0.38 to 0.76)
LST day	0.55 (1.85 to 1.25)	−0.06 (−0.26 to 0.13)	0.18 (−0.05 to 0.42)	0.33 (−0.41 to 1.10)	0.16 (−0.45 to 0.77)	0.01 (−0.24 to 0.26)
Spatial parameter						
$\sigma^2_i$	3.19 (2.01 to 3.99)	0.73 (0.42 to 0.89)	1.35 (0.99 to 1.62)	2.45 (1.81 to 3.03)	3.46 (2.52 to 3.66)	2.00 (1.22 to 2.26)
$r_i$ (degree)	0.91 (0.70 to 1.01)	0.06 (0.02 to 0.11)	0.88 (0.75 to 1.02)	0.15 (0.10 to 0.22)	0.44 (0.21 to 0.64)	1.30 (0.95 to 1.44)
<b>Second survey</b>						
Covariate						
Rainfall	0.88 (−0.03 to 1.86)	0.24 (0.04 to 0.44)	0.45 (0.24 to 0.66)	−0.15 (−0.79 to 0.42)	0.50 (0.00 to 1.09)	0.33 (−0.14 to 0.80)
NDVI	1.00 (0.35 to 1.66)	0.15 (−0.06 to 0.37)	0.57 (0.33 to 0.82)	0.07 (−0.48 to 0.63)	0.27 (−0.22 to 0.73)	0.60 (0.32 to 0.89)
Altitude	−1.53 (−3.05 to −0.08)	−0.03 (−0.24 to 0.18)	0.10 (−0.21 to 0.40)	0.05 (−1.34 to 1.36)	0.23 (−0.02 to 0.47)	−1.59 (−2.45 to −0.78)
LST night	0.05 (−1.07 to 1.18)	0.08 (−0.15 to 0.32)	−0.05 (−0.32 to 0.22)	0.72 (−0.64 to 2.02)	0.20 (−0.19 to 0.58)	0.10 (−0.57 to 0.78)
LST day	−0.36 (−0.83 to 0.09)	−0.16 (−0.38 to 0.05)	0.41 (0.20 to 0.63)	0.62 (−0.42 to 1.81)	0.47 (−0.01 to 1.01)	0.42 (0.09 to 0.69)
Spatial parameter						
$\sigma^2_i$	6.39 (5.25 to 6.57)	0.47 (0.12 to 0.63)	2.18 (1.57 to 2.50)	0.75 (0.32 to 1.42)	2.12 (1.95 to 2.43)	5.22 (3.89 to 5.66)
$r_i$ (degree)	1.02 (0.83 to 1.17)	0.12 (0.07 to 0.25)	0.31 (0.23 to 0.55)	0.90 (0.84 to 1.01)	0.47 (0.33 to 0.54)	2.07 (1.87 to 2.22)

Estimates are posterior median (95% credible interval). We standardised covariates by subtracting their expected value and dividing the difference by their SD to allow comparison of the effects of the predictors for a given country and survey. NDVI=normalised difference vegetation index. LST=land surface temperature.

**Table 2: Environmental factors and spatial parameter estimates, stratified by country and survey**

## Results

Table 1 provides a summary of the six African countries included in this study, including a descriptive analysis of the data obtained in the two national malaria surveys. From the first survey to the second survey, an overall decreasing trend in parasitaemia prevalence took place in all countries, except Liberia and Mozambique (table 1). In all countries, coverage of bednets and indoor residual spraying coverage have remained constant or were slightly increased in the second survey (table 1). While use of antimalarial drugs has remained constant, albeit heterogeneous, among countries, coverage of artemisinin combination therapies has increased in all countries except Senegal (table 1). We refer to an effect as significant whenever its credible intervals do not include 0 or the odds ratio intervals do not include 1. Coefficient estimates reported in the text were obtained with actual values of coverage of insecticide-treated bednets and indoor residual spraying and with socioeconomic and environmental factors, and differ from the estimates presented in the tables, which are based on standardised covariates to allow for comparisons of predictor effects by country. The appendix provides additional results of the spatial analysis.

Between 2006 and 2011, we noted a change in parasitaemia risk in children in Angola. While the first survey was done partly during the long rainy season, the second survey was done over almost all of the high transmission period. With the exception of the coast and some regions in the south, in 2006–07, parasitaemia risk

	Angola	Liberia	Mozambique	Rwanda	Senegal	Tanzania
Proportion of households with at least one ITN ( $ITN^+_i$ )	0.02	0.55	0.51	0.05	0.02	0.57
Proportion of households with at least one ITN for every two people ( $ITN^+_{i/2}$ )	0.09	0.05	0.15	0.11	0.09	0.11
Mean nets-to-people ratio ( $ITN^+_3$ )	0.01	0.10	0.05	0.10	0.01	0.01
Proportion of children aged 0–59 months who slept under an ITN the night before the survey ( $ITN^+_i$ )	0.11	0.02	0.08	0.61	0.02	0.10
Proportion of people who slept under an ITN the night before the survey ( $ITN^+_i$ )	0.73	0.15	0.15	0.11	0.81	0.08

The table shows the proportion of models that included each ITN indicator among all possible models. The models allowed the inclusion of one (or none) ITN ownership indicator and one (or none) use indicator. The number of possible models was therefore  $(3 + 1) \times (2 + 1) = 12$ . For example, when running the variable selection procedure on data from Angola, 73% of the models included, as an ITN indicator, the proportion of people who slept under an ITN the night before the survey. This indicator was then used in subsequent statistical models to assess ITN coverage and (spatial) effects. ITN=insecticide-treated bednet.

**Table 3: Posterior inclusion probability of ITN coverage indicators per country**

was high and almost evenly spread, reaching peaks of 80% (figure 1A). In 2011, parasitaemia was concentrated in specific regions of Angola, particularly in the northern part of the country (ie, the Zaire, Bengo, and Cuanza Norte provinces; figure 1B). Overall, the probability of a reduction in parasitaemia risk is higher than 50% throughout Angola (Figure 1D). Although we noted a slight decrease in risk in the Huila province (figure 1B), this region remains at high risk. Parasitaemia remained stable in the Cabinda province (figure 1B). Environmental



	Angola	Liberia	Mozambique	Rwanda	Senegal	Tanzania
Difference in rainfall	0.05 (−0.68 to 0.74)	0.15 (0.06 to 0.24)	0.26 (0.03 to 0.48)	−0.44 (−1.42 to 0.49)	0.53 (0.03 to 1.05)	0.32 (0.02 to 0.67)
Difference in NDVI	−0.02 (−0.28 to 0.26)	0.10 (0.01 to 0.19)	0.21 (0.05 to 0.37)	0.01 (−1.14 to 1.06)	−0.03 (−0.32 to 0.26)	0.05 (−0.16 to 0.26)
Difference in LST (night)	0.45 (0.03 to 0.84)	0.09 (0.01 to 0.17)	−0.08 (−0.27 to 0.10)	0.65 (−0.35 to 1.79)	0.23 (−0.16 to 0.61)	0.03 (−0.02 to 0.19)
Difference in LST (day)	−0.07 (−0.38 to 0.38)	−0.07 (−0.16 to 0.02)	0.26 (0.02 to 0.51)	−0.11 (−0.69 to 0.56)	0.14 (−0.23 to 0.55)	0.10 (−0.13 to 0.33)
Area type* (urban or rural)	−0.70 (−1.25 to −0.13)	0.00 (−0.11 to 0.10)	−0.28 (−0.47 to −0.08)	0.33 (0.28 to 0.89)	−0.22 (−0.66 to 0.16)	−0.34 (−0.60 to −0.10)
ITN	−0.64 (−0.98 to −0.30)†	−0.05 (−0.14 to 0.05)‡	−0.04 (−0.15 to 0.16)‡	−0.02 (−0.54 to 0.55)§	−0.34 (−0.64 to −0.05)†	−0.14 (−0.35 to 0.22)¶
IRS	−0.31 (−0.80 to 0.11)	..	−0.02 (−0.17 to 0.14)	..	−0.20 (−0.50 to 0.08)	−0.12 (−0.44 to 0.20)
Wealth index	−0.17 (−0.20 to 0.56)	0.01 (−0.08 to 0.10)	0.27 (0.12 to 0.43)	0.37 (−0.26 to 0.99)	0.22 (−0.11 to 0.57)	0.42 (0.21 to 0.63)
Artemisinin combination therapy**	0.48 (−0.42 to 1.31)	0.00 (−0.08 to 0.09)	0.37 (0.13 to 0.62)	0.07 (−0.89 to 1.29)	−0.17 (−0.66 to 0.27)	0.24 (−0.19 to 0.67)

Estimates are posterior median (95% credible interval). We standardised covariates by subtracting their expected value and dividing the difference by their SD to allow estimates to be compared within country. A negative effect for intervention strategies shows a protective effect. NDVI=normalised difference vegetation index. LST=land surface temperature. ITN=insecticide-treated bednet. IRS=indoor residual spraying. \*Dummy variable coded as 0=rural and 1=urban. †Proportion of people in the cluster who slept under an ITN the night before the survey. ‡Proportion of households in the cluster with at least one ITN. §Proportion of children aged 0–59 months who slept under an ITN the night before the survey. ¶Proportion of households in the cluster with at least one ITN per every two household members. ||Wealth index variable calculated as the proportion of households in the cluster reporting the lowest socioeconomic status (first quintile). \*\*Proportion of fever episodes in children in the region (first administrative level) treated with artemisinin combination therapy.

**Table 4: Effect of environment and interventions on change in parasitaemia risk**

	Number of infected children (last survey)	Number of infected children (difference)	Prevalence difference
Angola (2006–07 to 2011)	290 817 (285 030 to 296 603)	315 451 (307 507 to 318 395)	0.09 (0.09 to 0.10)
Liberia (2008–09 to 2011)	152 318 (149 148 to 153 486)	26 535 (23 930 to 28 139)	0.04 (0.03 to 0.04)
Mozambique (2007 to 2011)	1222 360 (1159 052 to 1225 668)	−3981 (−9258 to 1295)	0.00 (−0.00 to 0.01)
Rwanda (2007–08 to 2011)	18 639 (18 199 to 19 077)	13 457 (12 632 to 14 282)	0.01 (0.00 to 0.01)
Senegal (2008–09 to 2010–11)	53 935 (53 343 to 54 525)	36 433 (35 445 to 37 421)	0.02 (0.02 to 0.02)
Tanzania (2007–08 to 2011–12)	1168 438 (1121 895 to 1172 980)	503 169 (457 736 to 508 602)	0.06 (0.05 to 0.06)

Estimates are posterior median (95% credible interval). Number of infected children related to the second survey period (second column), estimated number of infection differences (third column), and model-based estimates of reduction in national level prevalence (fourth column).

**Table 5: Estimated number of infected children and prevalence reduction**

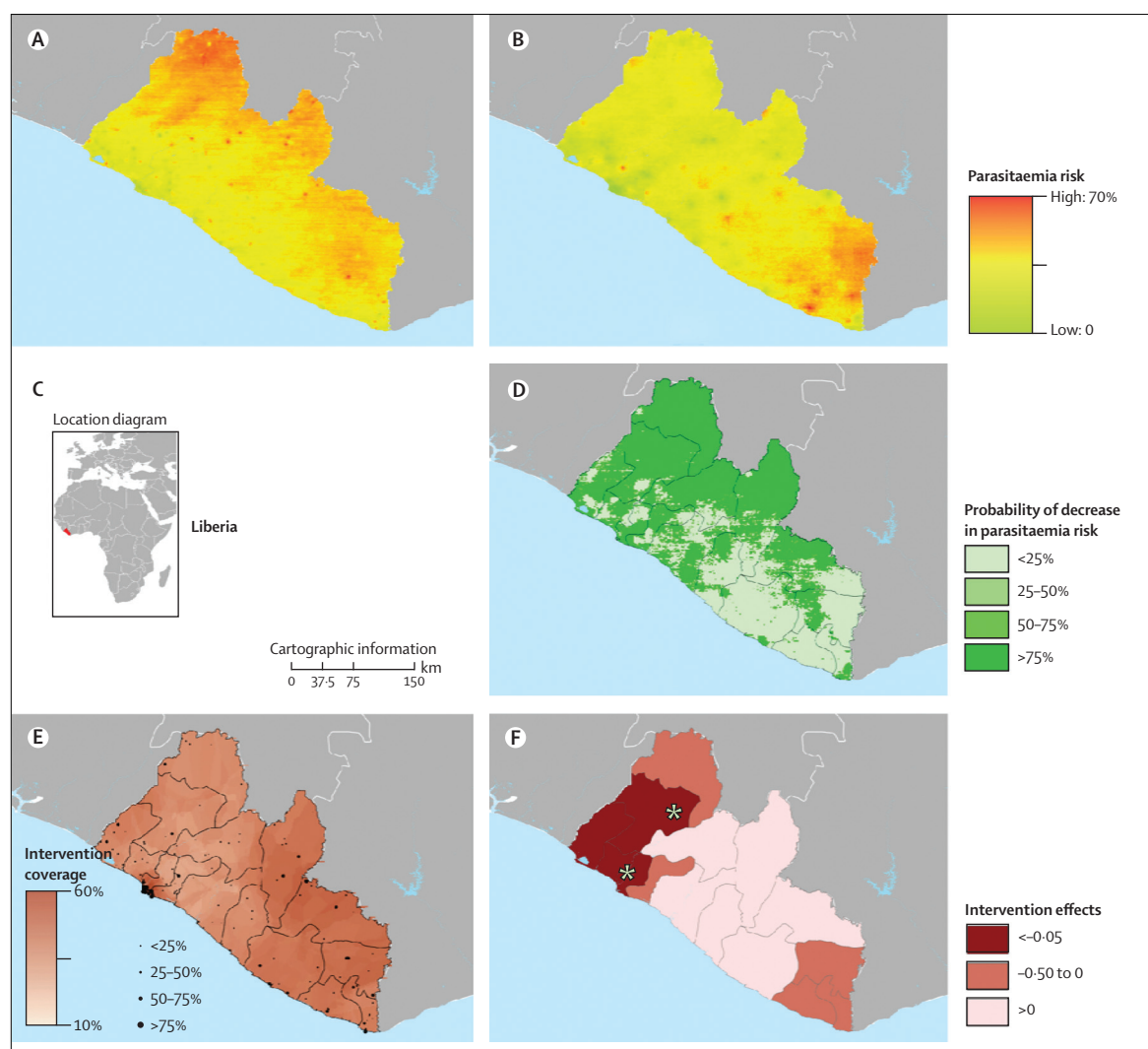
factors similarly affected parasitaemia risk in the two surveys and the spatial measures had similar estimates; however, the spatial variance estimate was higher in the model for the second survey (table 2). The measure of bednet coverage was the proportion of people who slept under a bednet the night before the survey (table 3). Among climatic variables, only change in night temperature was significantly associated with the change in parasitaemia risk (table 4). Rural regions are less likely to have had a decline in risk of malaria parasitaemia (odds ratio [OR] 0.49, 95% CI 0.29–0.88).

For intervention measures, effects produced were mostly negative (protective; table 4). For every 1% increase in coverage of insecticide-treated bednets, the OR of parasitaemia (second vs first survey) decreases by 5% (95% credible interval [CrI] 3–6). The effect of indoor residual spraying was not significant when modelled at country level (OR 0.34, 95% CrI 0.12–1.32; table 4).

Angola presents moderate to high coverage of insecticide-treated bednets in the outer part of the country and very low coverage in the inner parts, whereas coverage of indoor residual spraying is quite low, except for in a few regions (figures 1E, 1F). Use of insecticide-treated bednets was negatively associated with malaria change in the southeastern province of Cuando Cubango and in the coastal province of Benguela, whereas indoor residual spraying showed a significant effect mainly in the central part of the country (Malanje, Bengo, and Cuanza Norte provinces; figures 1G, 1H). The overall estimated number of infections in children younger than 60 months declined by 52.0% (95% CrI 50.7–52.5) from 2006–07 to 2011 (table 5).

Analysis of the two surveys done in Liberia showed that parasitaemia risk is spread throughout the country (figure 2). Environmental conditions do not seem to be clear drivers of malaria; none of them were significantly associated with the outcome at each timepoint (table 2). Spatial parameter estimates show similar values of variance and range in both surveys (table 2). The first survey (malaria indicator survey 2008–09) was done after the peak transmission period, whereas the second survey was implemented during the high transmission period (rainy season). Differences between the two surveys in terms of rainfall, normalised difference vegetation index, and night land surface temperature are positively associated with the change in the log odds of parasitaemia (table 2). Parasitaemia risk was high (60–70%) in the continental part of Liberia in 2008, and slightly lower in the coastal counties of Grand Cape Mount, Bomi, Montserrado, and Margibi (40–50%; figure 2A). We recorded the highest risk in Grand Gedeh, River Gee, and Grand Kru counties in the south (figure 2B); only the capital, Monrovia, has low risk (<10%).

Figure 2D shows the geographical pattern of change in risk in Liberia: whereas the probability of a decrease in



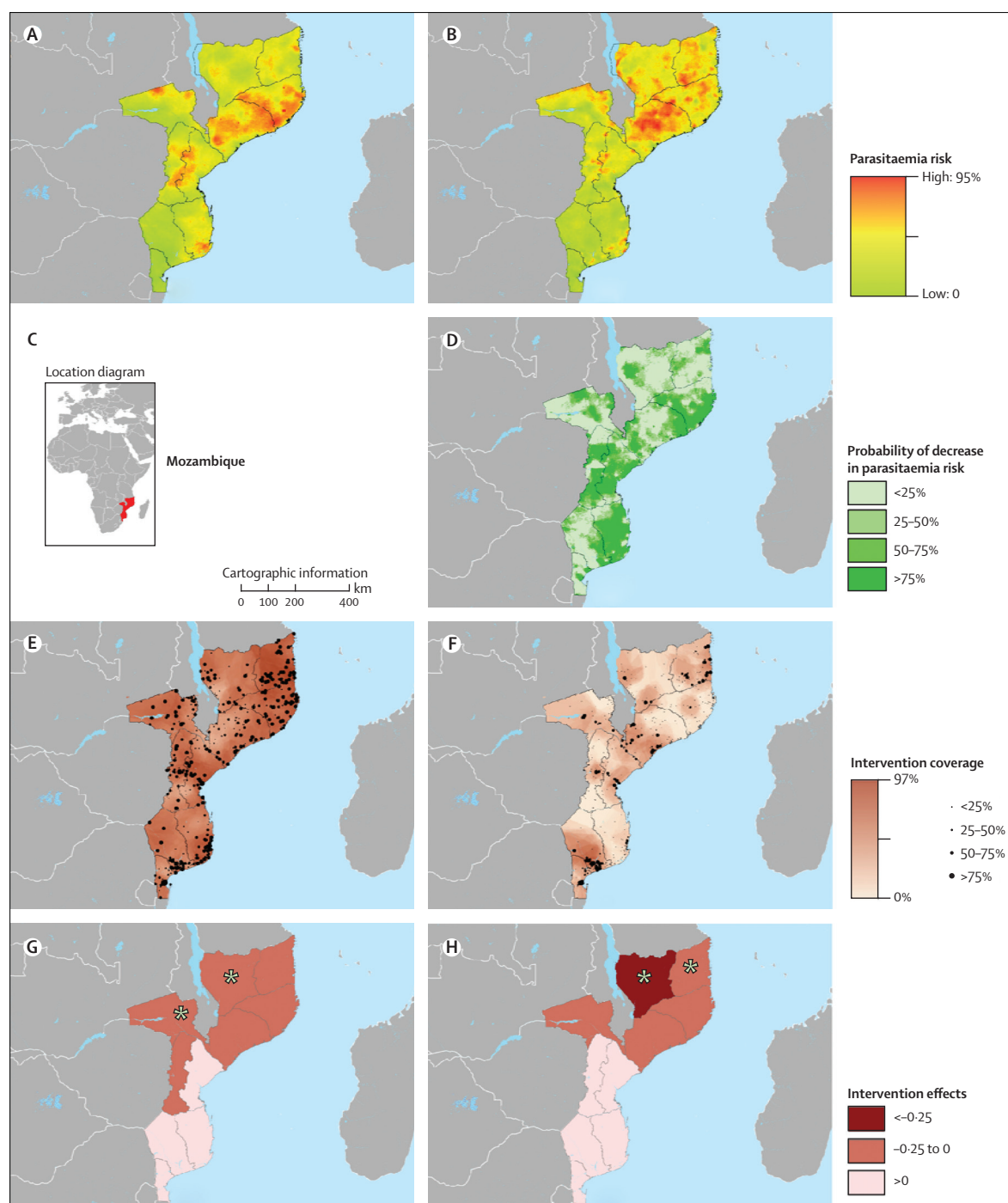
**Figure 2: Liberia**

Predicted parasitaemia risk in 2007 (A) and 2011 (B), location diagram and cartographic information (C), probability of observing a decline in the period 2007–11 (D), ITN coverage map for 2007 (E), estimated effects of interventions for 2007: ITN (F; median plotted). ITN=insecticide-treated nets. IRS=Indoor residual spraying. \*Statistically significant effect.

parasitaemia risk in the northwestern part of the country is greater than 50%, the probability is very low in the south. Malaria-control interventions in Liberia have been of low coverage. Indoor residual spraying, for example, has been implemented in only a few targeted regions, and coverage data were not obtained in the surveys; however, coverage of insecticide-treated bednets (selected as the proportion of households in the cluster with at least one bednet; table 3) is high (roughly 60%), mainly in the area of the capital (figure 2E). Association between insecticide-treated bednets and malaria change was moderate and not significant (OR 0.65, 95% CrI 0.43–1.25); however, the model with spatially varying bednet coefficients (figure 2F) showed a significant protective effect in the northern counties (Montserrado and Gbarpolu). The estimated number of infections in

children younger than 5 years reduced by 14.8% (95% CrI 13.4–15.8) from 2008–09 to 2011.

The two national surveys undertaken in Mozambique that included parasitaemia data were done after the rainy season. The second survey (demographic and health survey 2011) obtained data over a slightly longer period, partly explained by the larger number of surveyed clusters. We recorded the highest malaria risk in the provinces of Nampula and Zambezia, in the northern part of Mozambique (figure 3B). Southern parts of the country were characterised by low risk compared with the rest of the country (<10%), especially Maputo (city and province) and the Gaza province (figure 3B). The overall prevalence estimated from the second survey was similar to that estimated from the first survey. The main drivers of malaria parasitaemia are rainfall and normalised



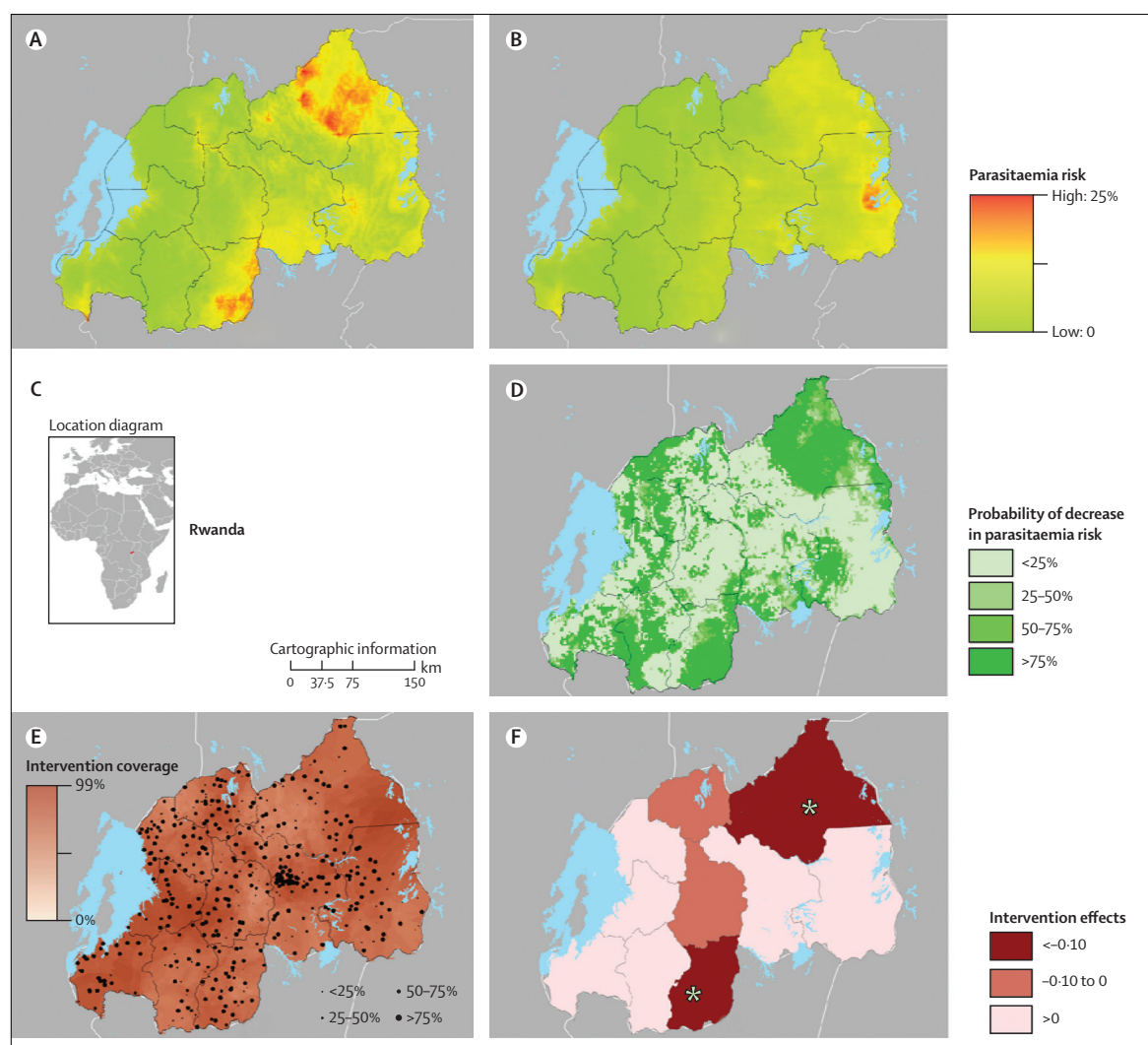
**Figure 3: Mozambique**

Predicted parasitaemia risk in 2007 (A) and 2011 (B), location diagram and cartographic information (C), probability of observing a decline in the time period 2007–11 (D), ITN (E) and IRS (F) coverage maps, estimated effects of interventions: ITN (G) and IRS (H; median plotted). ITN=insecticide-treated nets. IRS=Indoor residual spraying. \*Statistically significant effect.

difference vegetation index. The average day land surface temperature showed a significant association with parasitaemia in the analysis of the second survey (table 2). Higher estimates of spatial variance show higher variation of parasitaemia risk compared with 2007. Differences in

climatic conditions, such as land surface temperature (day), normalised difference vegetation index, and rainfall, between the two surveys were associated with a change in malaria risk (table 4). Rural regions were less likely to have had a change in risk of malaria parasitaemia





**Figure 4: Rwanda**

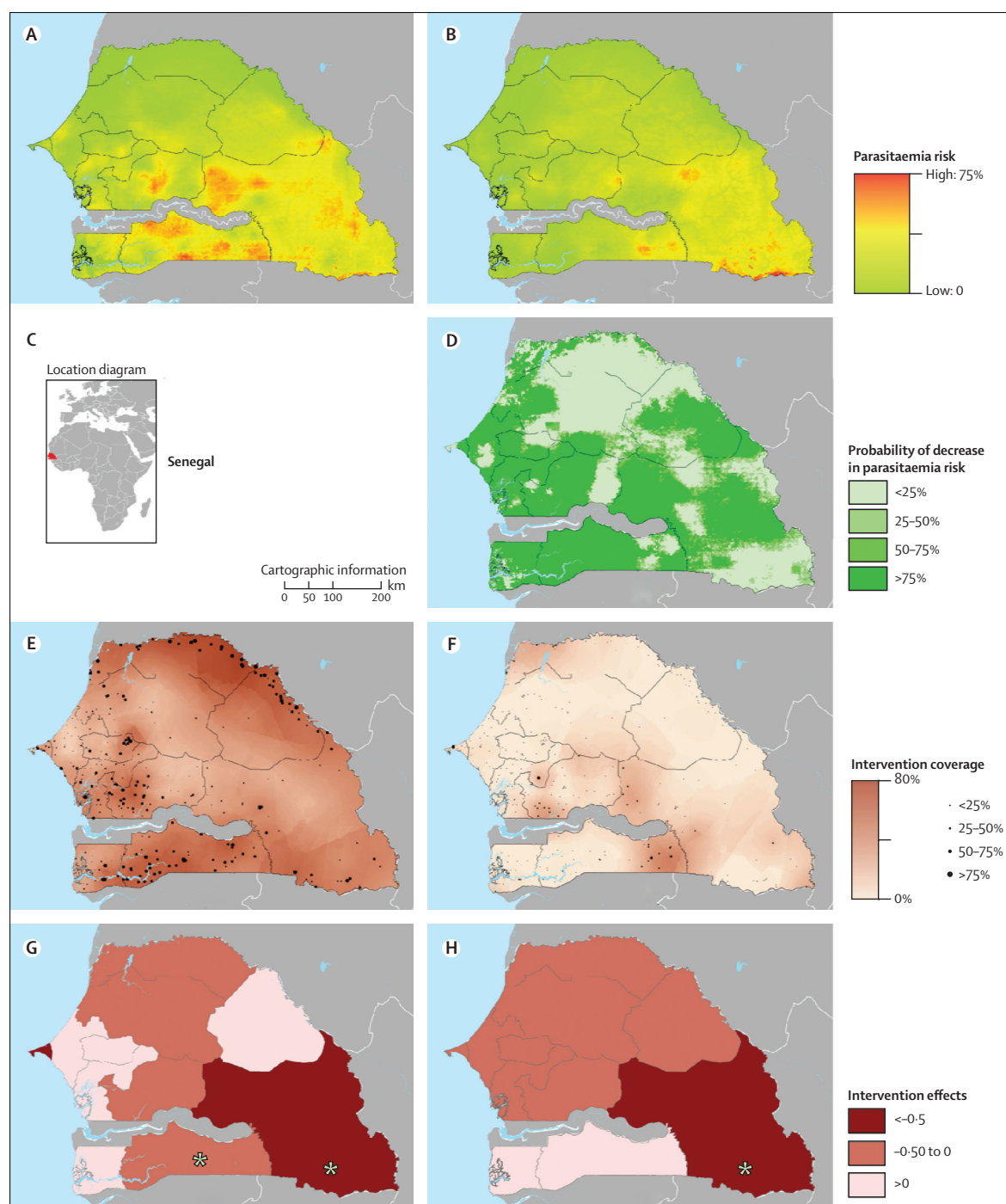
Predicted parasitaemia risk in 2008 (A) and 2011 (B), location diagram and cartographic information (C), probability of observing a decline in the time period 2008–11 (D), ITN (E) coverage map, estimated effects of interventions: ITN (F; median plotted). ITN=insecticide-treated nets. \*Statistically significant effect.

(OR 0.75, 95% CrI 0.63–0.92). The richest regions were most associated with a change in risk (1.52, 1.24–1.62).

Table 3 shows that, at country level in Mozambique, coverage effects of insecticide-treated bednets (ie, the proportion of households in the cluster who had at least one bednet) and indoor residual spraying were not significant (OR 0.83, 95% CrI 0.42–1.22 and 0.51, 0.31–1.13, respectively). Indoor residual spraying was implemented mainly in the southern part of Mozambique, but some other regions in the centre, particularly Zambezia province, showed high coverage of roughly 50% (figure 3E). In 2011, bednets were more common than residual spraying throughout the country, reaching 70% coverage in most provinces (figures 3E, 3F). The associations of bednets and indoor residual spraying with malaria change were negative (protective effects) in one northern province (Niassa); furthermore, the effect of

bednets was also significant in the Tete province and the effect of indoor residual spraying was significant in Cabo Delgado in northeastern Mozambique (figures 3G, 3H).

In Rwanda, the first (2007) demographic and health survey was done when malaria transmission was low, whereas the second survey (2011) was done during the short rainy season. Nevertheless, by comparison of the predicted parasitaemia maps in figures 4A and 4B, we noted a decreasing trend in malaria risk in some regions of the country. In 2011, the risk of parasitaemia ranged from 0 to 20%. The probability of a decline in parasitaemia was low (in view of the low or steady risk in most of the country), except in the Nyagatare and Gatsibo districts in the north of the east province, and in the Gisagara district in the southern province, where it is higher than 50% (figure 4D). The effect of environmental factors on the spatial distribution of parasitaemia risk showed no



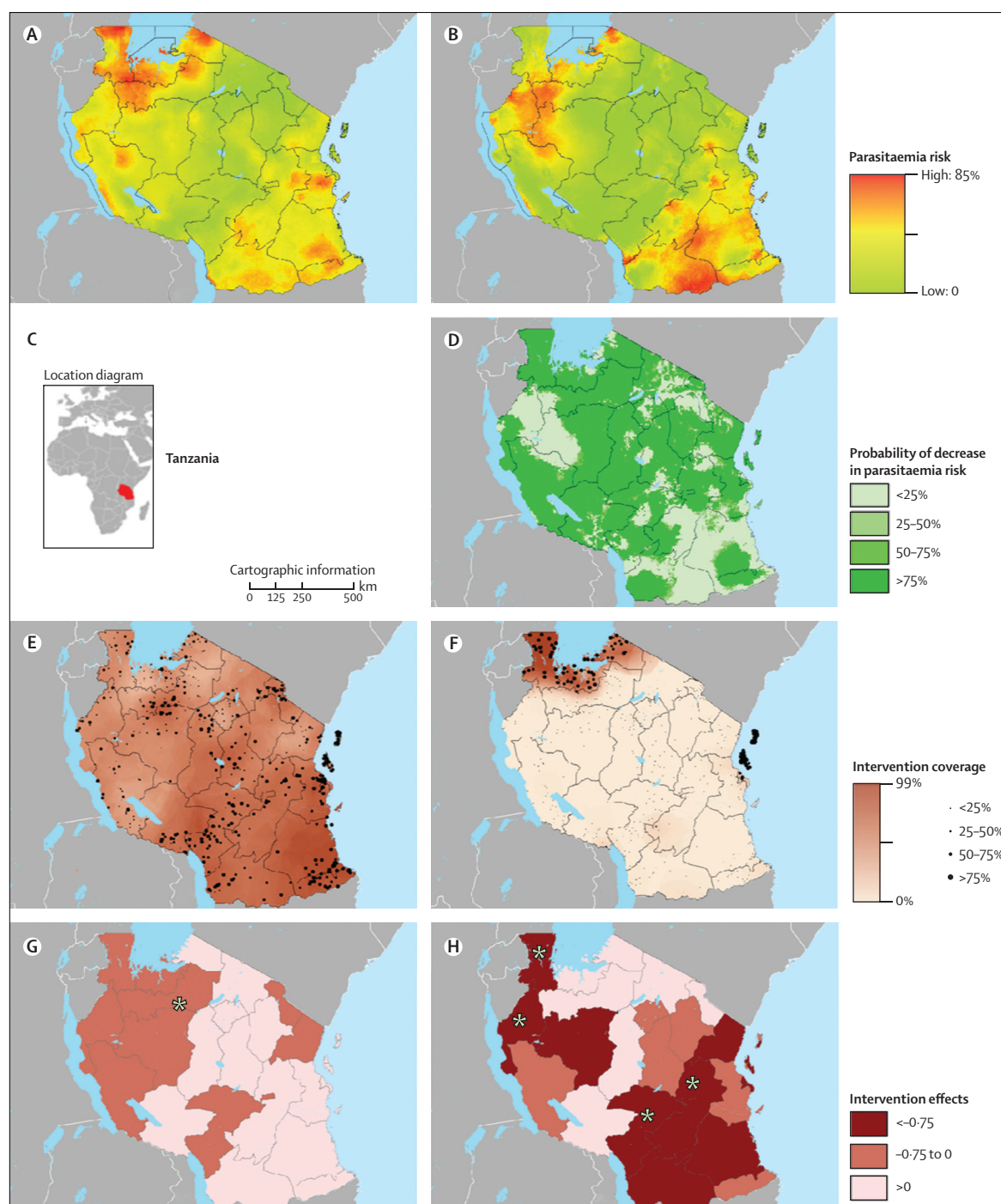
**Figure 5: Senegal**

Predicted parasitaemia risk in 2008 (A) and 2010 (B), location diagram and cartographic information (C), probability of observing a decline in the time period 2008–10 (D), ITN (E) and IRS (F) coverage maps, estimated effects of interventions: ITN (G) and IRS (H; median plotted). ITN=insecticide-treated nets. IRS=Indoor residual spraying. \*Statistically significant effect.

significant associations (table 4). Only elevation was negatively associated with malaria risk in the analysis of data obtained during the first survey (table 4).

Information about indoor residual spraying in Rwanda was not obtained during the surveys. Coverage of

insecticide-treated bednets coverage is very high, in terms of proportion of children in the cluster sleeping under a bednet, with very little variation across the country (figure 4E). We recorded the highest coverage rates in the Lake Kivu area and in the capital, Kigali



**Figure 6: Tanzania**

Predicted parasitaemia risk in 2008 (A) and 2012 (B), location diagram and cartographic information (C), probability of observing a decline in the time period 2008–12 (D), ITN (E) and IRS (F) coverage maps, estimated effects of interventions: ITN (G) and IRS (H; median plotted). ITN=insecticide-treated nets. IRS=Indoor residual spraying. \*Statistically significant effect.

(figure 4E). The effects of insecticide-treated bednets on parasitaemia risk are evident at the subnational level, particularly in the east and south provinces (figure 4F). However, the overall effect at country level was non-significant (table 4). The overall estimated number of

infections in children younger than 5 years in Rwanda decreased by 41.9% (95% CrI 39.4–44.5) from 2007–08 to 2010–11 (table 5).

Malaria in Senegal is concentrated in the central and southern parts of the country. The first survey (malaria

indicator survey 2008) was done after the rainy season, during a period in which transmission decreases from high levels. The second survey (demographic and health survey, 2010) was done over a 5 month period, of which 1 month was during high transmission. However, parasitaemia risk in some known pockets of transmission, such as the regions of Tambacounda, Kaffrine, and Kolda in the south, has greatly decreased (figures 5A, 5B). The probability of a decline in parasitaemia risk is more than 50% in most regions in Senegal, except for the Kedougou region in the south and the Saint-Louis region in the north, where the risk remained fairly constant, although at low levels (figure 5D). The main environmental drivers in Senegal are rainfall and normalised difference vegetation index (table 2). The association between these two climatic features and parasitaemia was much stronger in the first survey, whereas normalised difference vegetation index was not significantly associated with malaria parasitaemia in the second survey (table 2). We noted a smaller spatial variance, but higher range, in the second survey than in the first survey (table 2).

Table 3 shows that the proportion of people in the cluster sleeping under a bednet is one of the measures of bednet coverage that best describe the change in malaria risk in Senegal. Most of the clusters sampled along the Senegal River (at the border with Mauritania) show high coverage, as do most of the clusters in Kolda and Kaolack-Kaffrine (figure 5E). Indoor residual spraying is limited to some regions of Saint-Louis in the north and at the border between Kolda and Kedougou (figure 5F). A 1% increase in coverage of insecticide-treated bednets was associated with a reduction of 2% (95% CrI 1–4) in the odds of parasitaemia. The effect of indoor residual spraying on parasitaemia change at country level was not significant; however, if estimated at area level, this intervention has a higher and significant effect in the Tambacounda region (figure 5H). Similarly, coverage of insecticide-treated bednets was associated with a significantly reduced risk in both the Tambacounda and neighbouring Kolda regions (figure 5G). The estimated number of infections in children younger than 5 years decreased by 40·3% (95% CrI 39·2–41·4) from 2008–09 to 2010–11.

We modelled parasitaemia in Tanzania separately for the mainland and the islands. Risk of parasitaemia on the islands was very low (0–5%) in 2008, and slightly lower in 2012 (figures 6A, 6B). In mainland Tanzania, the risk of parasitaemia is high, reaching up to 70–80% in the northern and southern regions (figures 6A, 6B). Figure 6D shows that the probability of a decrease in parasitaemia risk during the second survey is greater than 50% in most regions of the mainland. In some other regions, we detected an increase in the risk (figures 6A, 6B). Additionally, we estimated a positive association between change in malaria risk and rainfall (table 4).

Coverage of insecticide-treated bednets ranges from 25% to 95%, with the highest estimates obtained in the urban area of Dar es Salaam and the large islands of

Zanzibar (Unguya and Pemba; figure 6E). Indoor residual spraying is mainly implemented in the Lake Victoria area, and on the islands of Zanzibar and Dar es Salaam (figures 6E, 6F). Indoor residual spraying was effective in the lake area and in two southern provinces (Morogoro and Iringa), and on the islands (figure 6H). Dar es Salaam and Shinyanga provinces mostly benefited from the bednet intervention (figure 6G). At country level, insecticide-treated bednet and indoor residual spraying interventions were not significantly associated with change in malaria risk in Tanzania (table 4). The estimated number of infections reduced by 30·1% (95% CrI 27·4–30·4) from 2007–08 to 2011–12 (table 5).

## Discussion

Our findings showed country-specific spatial patterns of changes in parasitaemia risk between the two surveys. For example, a decline in risk was shown throughout most of Angola. In Senegal and Rwanda, the relation between environmental factors and malaria risk became less evident in the second survey, probably explained by the high coverage of malaria control interventions that blurs the strong associations between malaria and climate. In other countries where the change in risk varies substantially from one area to another (eg, Tanzania), the overall risk has decreased, but there are clusters of high parasitaemia, leading to an estimated increase in spatial variance. Mozambique is the only country in which a significant reduction was not shown in the model-based estimates of prevalence and number of infections in children younger than 5 years. In some regions of Tanzania, we noted an increase in parasitaemia, possibly due to the scarce coverage of interventions and the positive association with the increased amount of rainfall during the second survey, which was done during the long rainy season. In countries where the surveys were done during similar seasons (eg, Angola and Rwanda), the decline in risk is not presumed to be due to seasonal variations, as confirmed by the absence of associations of environmental and intervention effect on change in parasitaemia risk. Roll Back Malaria have recommended that surveys take place during the highest transmission season, but this is not always feasible because of logistical issues and a scarcity of human resources to reach remote areas. For this reason, surveys might lack comparability, unless idiosyncrasies of environmental conditions of the individual surveys are taken into account.

To estimate the number of children younger than 5 years with parasitaemia, on the basis of both first and second surveys, we used readily available Afripop population data for 2010. Use of year-specific population data would lead to more estimates of increased accuracy for children infected in the two surveys, but this information is not available at high spatial resolution. In view of the average annual rate of population growth in the six countries (2·63–3·82%),<sup>20</sup> our data tend to underestimate the burden reduction when expressed in absolute number of infections.



Coverage of indoor residual spraying was assessed on the basis of the proportion of households within a cluster that were sprayed in the last 6 months. Unfortunately, the surveys have little information about this intervention compared with insecticide-treated bednets. This scarcity of information is probably due to late implementation of the intervention, late introduction of the question in the survey questionnaires, or absence of this intervention. Coverage of insecticide-treated bednets was measured by several indicators because no uniform consensus exists about the definition of bednet coverage. The employed Bayesian variable selection procedure enabled inclusion in the model of the bednet coverage measure with the highest posterior probability, so as not to miss important effects of bednets within a country. We assessed the effects of interventions at subnational level with a geostatistical model with spatially varying coefficients because of the known spatial nature of intervention (ie, community) effects and because we assume that neighbouring regions are affected similarly by a specific intervention. By contrast, regions located further away from one another might show different effects because of different levels of endemicity. In fact, people's protective behaviour, levels of insecticide resistance, or priority regions for malaria control might change in space, thus affecting intervention effects. Intervention coverage is widely considered to be a predictor of malaria risk. However, malaria risk, and therefore endemicity levels, can affect intervention coverage, because regions of high endemicity might have high coverage because of intensified malaria control and increasing risk awareness. As such, estimates of intervention effects might be conservative. We addressed this issue with the estimation of intervention effects at local scales. We used the administrative division as the unit of analysis for estimation of intervention effects in space. In most of the countries, this division corresponds to the health division at which decisions can be made; furthermore, it represents the smallest regions, with at least three observations, sufficient for estimation of spatially explicit intervention effects.

Intervention effects varied from one country to another and geographically within countries. The association between intervention (insecticide-treated bednets and indoor residual spraying) coverage and their spatial effects is not straightforward. Our analysis shows that regions with relatively low coverage sometimes have larger effects on the reduction of parasitaemia risk in space than do those with higher coverage. This finding might be due to different endemicity levels; in fact, in regions with low endemicity, moderate intervention coverage might be sufficient to show an effect on parasitaemia reduction. Furthermore, strong effects do not necessarily show significance: in our analysis, most regions with low coverage did not show a significant effect, although the size of the effect is large. In some regions, intervention effects were significant, but no

decline in prevalence was detected. However, there is an elapsing period between decline in transmission intensity (eg, vectorial capacity) and potential decline in the prevalence of population infection, especially in regions of high transmission. This decline in prevalence is because indoor residual spraying and insecticide-treated bednets directly affect mosquitoes' feeding cycle and death rates, leading to immediate changes in the vectorial capacity; reduction in the number of infective mosquito bites leads to reduction in infection prevalence at the population level. In other regions, no significant association between intervention measures and malaria risk was detected. This finding might be explained by other factors, such as behaviours of human beings, mosquito behaviours (higher or lower outdoor biting rates), pyrethroid vector resistance, or the physical integrity of bednets (eg, presence of holes). However, bednets have a variable lifespan in terms of physical condition, residual insecticidal effect, and perceived usefulness, dependent on the geographical and cultural context;<sup>21</sup> therefore, a modelling approach is not straightforward. We are working on ways to incorporate information about net conditions into geostatistical analyses. The variability noted in the effects of indoor residual spraying and insecticide-treated bednets supports the need to assess intervention programmes at local scales. These results provide important information about the regions that require closer monitoring and about factors that weaken intervention effects.

Heterogeneous bednet benefits on several health outcomes (eg, malaria prevalence, child mortality) have already been documented in previous studies.<sup>8,22,23</sup> One of these investigations<sup>8</sup> pooled seven malaria indicator and demographic and health surveys to assess the effect of household bednet ownership or use on parasitaemia prevalence in children younger than 5 years. Four countries had a significant association between bednet ownership and parasitaemia prevalence: the relative reduction in parasitaemia prevalence ranged between 29% and 45%. Three countries did not have a significant effect (mean OR 0.99–1.11). The same study used data from 29 demographic and health surveys to assess the association between household bednet ownership and child mortality. There were statistically significant reductions in five surveys: the relative reduction in child mortality ranged between 30% and 69%. The remaining surveys did not show a significant effect (mean OR 0.24–1.68). In our study, we estimated the spatial effects of both indoor residual spraying and insecticide-treated bednets in different regions and contexts, making full use of the information gathered in the surveys rather than obtaining an overall measure of association between intervention coverage and changes in malaria risk over time.

We used the reported proportion of fever episodes in children younger than 5 years treated with artemisinin-combination therapies as a proxy for coverage of effective antimalarial treatment. However, this variable was not



**Panel: Research in context****Systematic review**

Spatial analysis to identify the risk of malaria and guide interventions has been a productive research area in the past few years (eg, Mapping Malaria Risk in Africa project, Malaria Atlas project). Initial mapping efforts were based on historical data that were heterogeneous in survey seasons and in sampled age groups. Malaria indicator surveys are nationally representative surveys done during seasons of medium and high transmission and focusing on a specific age group (eg, children younger than 5 years). Hence, these surveys provide the most precise benchmark of progress towards internationally agreed targets, allowing for estimation of the geographical distribution of parasitaemia risk and malaria burden. We searched PubMed on Sept 2, 2013, with keywords "Malaria Indicator Survey" and "geostatistics". Geostatistical analyses of malaria indicator surveys have produced spatially explicit estimates of disease risk and of the number of infected children younger than age 5 years,<sup>14,15,29-32</sup> but none has assessed the change over time. We therefore undertook this study, with all the countries in sub-Saharan Africa with publicly available data from two malaria indicator or demographic and health surveys with specific malaria questions, done at different times (2006–08 and 2010–12).

**Interpretation**

To our knowledge, this is the first study presenting spatial estimates of the probability of malaria risk reductions and of the spatial effects of interventions in various sub-Saharan countries after adjustments for climatic and socioeconomic factors. These estimates can be used to assess the accuracy of mathematical models that predict malaria risk under different levels of intervention coverage. Both estimates and maps provide essential information for national malaria control programme managers in the monitoring and planning of future interventions.

significantly associated with decreases in parasitaemia risk. One reason could be identified in the scale-up of diagnostic testing.<sup>4</sup> Overall, urbanisation and socioeconomic status showed important associations with changes in malaria risk.

Vector ecology and changes in species distribution are also important to changes in transmission. Existing georeferenced data for vector and species occurrence (eg the Malaria Atlas, VectorMap, and MosquitoMap Projects) are sparse and not contemporary to the parasitaemia national surveys. Some attempts have been made to provide a global map for dominant malaria vectors.<sup>24</sup> However, the information provided is not available at the spatial resolution at which we did the present analyses.

We produced coverage maps to assess progress towards universal coverage and identify regions that have been successful in scale-up of key malaria control interventions.<sup>25</sup> The maps produced can aid national malaria control programmes in future intervention

delivery. We considered countries in which 100% of the population is at risk; however, the heterogeneity in intervention coverage shows the need to spatially assess progress towards universal coverage, with identification of regions where coverage is particularly low.

Prevalence survey data are valuable for assessment of progress towards disease elimination because they aid study of the pattern of change in malaria in space and time, and estimate the contribution of interventions on changes in parasitaemia risk. Prevalence is easily measured and its widespread use makes it suitable for monitoring and evaluation.<sup>26</sup> However, assessment of changes in disease burden includes other indicators that measure incidence and mortality; this task is not easy in many sub-Saharan countries where health information systems and vital statistics, including causes of death, are still very weak.

Malaria indicator surveys are either run as stand-alone surveys or incorporated into demographic and health surveys. Although costs of survey implementation would be reduced, combining demographic and health and multiple indicator surveys in a unique survey would extend the field study period to seasons of low or no transmission for malaria. Inclusion of these seasons might result in an underestimation of the prevalence and could introduce bias in the spatial pattern of malaria risk. When malaria indicator surveys are run independently, they are usually done during the season of high transmission to capture the highest number of infections. However, undertaking surveys during high transmission seasons is sometimes not feasible, and the peak of transmission is subject to geographic and between-year variability. The use of rolling cross-sectional surveys can provide a potential solution to these issues. Sampling routinely throughout the year within the same region allows seasonality in transmission to be estimated and seasonality-adjusted prevalence estimates to be obtained (eg, seasonality adjusted prevalence maps). A continuous survey has already been proposed and implemented in the context of demographic and health and nutritional surveys,<sup>27</sup> and a year-long rolling multiple indicator survey has been implemented in one district of southern Malawi.<sup>28</sup> Limiting the collection of household data to a few key malaria indicators reduces the time and costs implied by a rolling survey. However, their feasibility at national scale remains to be investigated.

To our knowledge, this is the first study to present spatially explicit estimates of the probability of reductions in malaria risk and of spatial effects of interventions in six sub-Saharan countries, after adjustment for climatic and socioeconomic factors (panel). These estimates can be used to assess the accuracy of mathematical models that predict malaria risk by different levels of intervention coverage, but they are foremost important for managers of control programmes to identify the regions that need close monitoring and the factors interacting with parasitaemia trends and intervention effects.

# Contributors

FG processed and analysed the data, interpreted the results, and wrote the manuscript. PV conceptualised the project and assisted in the statistical analysis. SK, AS, JU, MT, and PV revised the manuscript, and provided important intellectual content. All authors approved the final version of the manuscript.

# Declaration of interests

We declare no competing interests.

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